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ADP021120

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TITLE: Proceedings of the International Display Manufacturing Conference [2nd] Held in Seoul, Korea on 29-31 January, 2002

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I-15.1: Specialty Application of Flat Panel Displays *

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Abstract

Many display applications involve low unit volumes yet must be economically viable. Exotic displays--less than 1000 units worldwide--are used in advertising, entertainment, public service, scientific, and defense systems. Such specialty applications of flat panel displays are analyzed along with their business models. These niche markets are, perhaps paradoxically, associated with significantly higher performance requirements than incorporated into mass market products. It will be shown that display technology is driven, to a disproportionate degree, by the design and manufacturing efforts undertaken to address these niche market products. That is, the engine of progress in flat panel displays is powered by specialty applications.

Introduction

Specialty applications are distinguished from commonalty by some unusual quality. Market size is one measure of distinction. Mass markets define commonalty display applications as those having annual unit sales of millions; specialty applications are exotic with annual sale of one unit to hundreds, or niche, tens of thousands. Product profit margin is another distinction, with specialty displays often commanding significantly more. Performance drives the design and pace of technology evolution for displays used in specialty applications. However, unit cost drives the design and incremental rollout of innovations in commonalty applications. Schedule for specialty applications tends to be commanded by the achievement of the desired level of performance; schedule for commonalty applications is commanded by rigid (e.g. 18 month) product cycles. Commonalty applications get big, flashy marketing budgets; specialty applications often get no public attention at all.

Some say we need no more new display technology and that all applications, specialty and commonalty alike, can be satisfied with performance and prices already available. However, the natural world display scene and the human vision system (HVS) that evolved in it are dramatically better than anything build during the mere 100 years during which humans have been building electronic displays.

The difference in performance between Nature's display system and human attempts to emulate it is described. Specialty applications include areas like avionics cockpits, ultraresolution, and building façades. Progress in such exotic areas typically enables future commonalty applications.

Business Models

Economic viability for low unit volume products, such as specialty displays, requires a continual rethinking of the business model. High volume electronics manufacturing evolves rapidly and changes continually as companies, countries, and cultures strive towards their respective goals. Exotic and niche markets must adjust, or go without product. Factors such as expertise of staff, maturity of industry, marketing of good will, contribution to national defense, and cultural preferences interact chaotically yet synergetically.

Fab Time Purchase. Viable manufacturing display companies focus on mass markets to amortize the cost of production facilities. A new high-volume thin-film transistor (TFT) active matrix liquid crystal display (AMLCD) manufacturing facility (fab) requires a capital investment of about $1B, lasts some 5-7 yrs, and burns operating expenses at a rate over $100M/yr. Sales over these 5-7 yrs need to total about $2B, requiring production of 10M 15in.-equivalent AMLCDs at the current market price of about $200. Thus, the mass-market fab needs to average 30,000 to 40,000 shippable 15in.-equivalent units per week.

Exotic markets need the same fabrication quality capability, but do not have the volume, on their own, over which to distribute the fab cost. Aircraft production programs, for example, require just 1 to 20 units per week, but, perversely, at the much higher, avionics-grade.

The best hope for exotic and niche markets in such circumstances is to purchase fab time—i.e. pay the value of the "lost" commercial production during the days used for specialty product runs. This hope can only be realized if the niche market can establish a business arrangement consistent with the primary need of the fab to service mass markets.

Expertise and Intellectual Property. Viable companies need to maintain their market position in terms of technical expertise. They either stay up with technology and expand the abilities and skills of their engineers and technicians, or go out of business.

Specialty applications provide challenging design and fabrication problems (as compared to the routine product evolutions) and are demanded by the best people as a non-monetary compensation for career growth. Niche markets may be viewed as opportunities for fabs to be paid to develop intellectual property for future mass market product cycles and to address workforce retention and improvement.

Maturity. The first AMLCD fabs in the 1980s and 1990s were vertically integrated with design and all manufacturing steps located in one facility. Raw materials and manufacturing tools were transported from a variety of places on the planet to one site where all of the value added

* SID Digest for The 2nd International Display Manufacturing Conference, Seoul, Korea, 29-31 January 2002.

needed to make a display was accomplished. However, the diverse materials and processes involved improved at different paces and their separate evolution was inhibited by the presence of the others. The skill set for product design was different from manufacturing. Fabrication of controller boards, backlights, color filter plates, TFT plates, automatic handling equipment, cell assembly, display assembly, etc. is now typically done in specialized facilities and other electronics is left to the OEM of the end-user product. Design is done at the OEM, which interfaces to feature sets wanted by customers—usability and price. Manufacturing of the display component of the OEM design is the focus of the TFT fab, which interfaces to the sub-component fabs for materials, tools, and processes. For specialty applications separate companies—aggregators—now exist to help several exotic market OEMs design products using a common yet custom display and to establish a viable production run attractive to the display manufacturing facility.

Marketing. Businesses can establish goodwill with the public based on work performed in exotic and niche markets. Saab in Sweden, for example, uses it Gripen jet fighter in its automobile advertisements. LG in Korea and Philips in The Netherlands could use their fighter-cockpit-grade AMLCDs manufactured their LG-Philips LCD fab in Kumi, Korea to advertise their consumer electronics products. IBM and Toshiba can use the ultraresolution 8-9 megapixel, 20-22 in. AMLCDs they developed for niche markets in digital cinema, medical radiology, and scientific visualization (e.g. of Hubble telescope images) to help sell the pubic on the superior quality of their mass market AMLCD notebook computers, monitors, and appliances.

Defense Contribution. All countries are concerned with their own national security and sharing the cost of developing, fielding, and maintaining the necessary weapons systems with their allies. Companies reliant on international commerce depend upon defense establishments, domestic and allied, to establish a secure framework within which their businesses can operate. Thus, a willingness to design and manufacture specialty display components for military applications exists at many companies albeit, of course, at a profit for their shareholders. Indeed, many companies use their work on heroic military projects (see Figure 1) to advertise their civil products and to convey to the public that they are contributing to national defense.

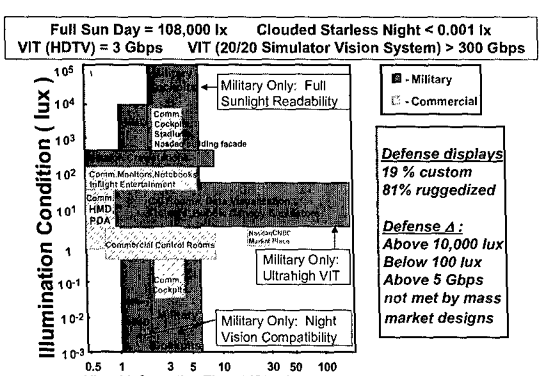

Figure 1. Exotic market drivers for defense displays: illumination conditions and visual information thrust [1].

Culture Factor. During the early 1990s the U.S. Department of Defense (DoD), via its contractors, sought to establish production of specialty displays for combat cockpits. The only mass production lines were in Japan. The Japanese, due to a cultural issue, declined to undertake such military-unique activity. The performance required was technologically possible but beyond that needed even in the difficult niche market of commercial aircraft cockpits, which the Japanese were working. Examples included Hosiden in Kobe, Japan (now Philips Components Kobe) work with Honeywell in Phoenix AZ on the new Boeing B-777 cockpit and with Rockwell for the Space Shuttle cockpit upgrade, and recent Sharp work with Rockwell Collins in Cedar Rapids IA on the B-767 cockpit upgrade from CRTs to AMLCDs. Negotiations between US and Japanese officials led only to a so-called dual use policy, according to which Japanese-produced displays could be put into a military application if and only if designed for a non-military application and used there first. Thus, Rockwell Collins, for example, can re-integrate its B-767 commercial avionics-grade AMLCD into the C-17. This situation left critical defense programs without any source whatsoever for combat-grade AMLCDs.

The DoD determined that combat-grade flat panel displays (FPDs), especially AMLCDs, were absolutely essential to advanced human interfaces in combat and proceeded to obtain its combat cockpit displays during the 1990s by establishing several small domestic fabs, including Optical Imaging Systems in Northville, Michigan and dpiX LLC in Palo Alto, CA, and by funding work at others such as ImageQuest in Fremont CA and Litton in Toronto, Canada. These four domestic fabs were not economical as display manufacturing facilities. They were viewed as investments to achieve greater fighter pilot productivity. The optimization that controls decision-making is the one for the final product—the fighter aircraft—not a relatively low cost component like a display. Thus, $150 million for combat avionics-grade AMLCDs fabs is affordable, if necessary, to support combat cockpit programs totaling over $150 billion.

Without these four domestic fabs the DoD would have had to go without the ultra-high-performance FPDs (combat fighter cockpit AMLCDs) necessary to the development of a new generation of combat aircraft and the upgrade of current cockpits with FPDs. Nonetheless, a more affordable approach became possible at the end of the 1990s as commercial AMLCD fabs appeared first in Korea and then Taiwan. Neither the Koreans nor the Taiwanese have the cultural aversion of the Japanese to working military-unique programs. Thus, the business arrangements recently established between, e.g. American Panel Corporation in Alpharetta GA and LG-Philips LCD in Kumi, Korea and Planar in Beaverton OR with UNIPAC (now AU) in Hsinchu, Taiwan enable the specialty market of combat cockpit-grade AMLCDs to be addressed without the additional burden of a cultural roadblock.

The four domestic US fabs were unable to reduce their costs for shipped display products as much as the Asian manufacturers and, thus, went out of business. Even a small AMLCD fab must sell most of its capacity to non-military markets. The business model written in 1991 by DoD noted that the military would consume just 5% of output from the smallest, $200M, fab that had proven viable in Japan.

Current Displays vs. Nature

The grand challenge for display technology is to match the real world. Hopper [2,3] examined maximum resolutions in natural world scenes perceivable by the human vision and the pace at which presently inaccessible portions human capacity may be realized in devices.

The natural world display system (NWDS) is defined by ignoring limitations of present-day knowledge and understanding of hardware, software, computers, or human factors. That is, it is presently impossible to build a display matching the NWDS, but that system nonetheless exists and should be characterized to aid analyses and goal setting for both specialty and commonalty applications. Key aspects of NWDS representation via sampling are spatial (picture elements, pixels), intensity (grayscale levels), and temporal.

Spatial Representation of Nature's Display

The NWDS fills the entire solid angle of 4π sr about a point. This 4π sr field-of-view may be represented geometrically as an ensemble of solid angle samples whose cross sections satisfy the condition that there are no gaps. Spatial samples whose cross sections (pixels) are hexagons, triangles, et cetera, leave no gaps; but squares and circular cones introduce spatial sampling error. Hopper [1,2] demonstrates that sampling (pixelation) of the 4π sr photon flux field may be represented by N_{pixel} samples, where

$$N_{pixel}(\beta) = 5.3465 \times 10^{11} \beta^{-2} ,$$

for β in arcseconds. Each sample has a solid angle of β^2. A display in the shape of a sphere would require N_{pixel} pixels to represent a 2-D scene to an acuity, or fidelity, equal to β. Examples are listed in Table I.

A more extensive analysis would introduce variable pixel sizes and types (as in the retina of the eye). Ensembles and distribution functions would then be needed. Future displays may have variable pixel sizes and types; but current devices typically have but one pixel size and type, with no variation across the display surface. Of course, pixels of constant size, may have variable angular size when viewed from different points (e.g. design eye or optics aperture).

Error terms (distortions in perception) may result from a mismatch of the solid angle of the display at the viewers' eye compared to the solid angle collected/sampled by the sensor or generated by the image generator/processor.

Table I. Pixels in 4π steradians as a function of acuity; plus corresponding pixel density and pitch at 610 mm (24 in.).

Acuity, β (arcseconds)	Name	Pixels (in 4π sr)	Density (in^{-1})	Pitch (μm)
100	Image perceivable	53 Mpx	86	296
84	E-letter, orientation	76 Mpx	102	249
50	20/20 vision	214 Mpx	172	148
25	2 discs/bars	855 Mpx	344	74
14	Detect square	3 Gpx	614	41
5	Glint, stars	21 Gpx	1,720	15
2	Vernier	134 Gpx	4,297	6
0.5	Line > 1°	2 Tpx	17,189	1.5

Also, one must not ignore a consideration of the differing shape and size of pixels in sensors versus displays. Specialty displays are often the result of exploitation of the state-of-the-art in sensor technology. Examples of such combined analyses might include:

- hexagonal sensor pixels (e.g. retina in the HVS) combined with rectangular pixels (active matrix FPDs);
- square sensor pixels (CCD cameras) combined with circular Gaussian spot on CRTs or with rectangular active matrix FPD pixels.

Such pixel shape, size, and type mismatch introduces terms into the sampling error function. Of course, with present day manufacturing techniques it is easier to produce display and sensor devices whose pixels that are either circular (CRT), or have 90° corners (FPD), rather than 120° or 60° corners. Thus, all current-day display devices introduce image representation errors. The NWDS representation error functions may become of concern unless definition is near infinite, with very small pixels having $\beta < 0.1$ arcseconds.

Intensity and Temporal Representation of NWDS

Within each pixel are two further sampling domains: intensity and time. The ideal discrete representation of the NWDS requires some 54 bits for intensity variations, or 18 for each of three primary colors. Current displays typically render 24 bits, or less, in the images arriving at the eyes of the viewer.

Temporal sampling needs to be greater than 90 Hz per frame to avoid motion artifacts. Current display applications typically achieve 48-72 Hz.

Deficiencies of 20/20 Vision

An acuity metric such as 20/20 vision (β = 50 arcseconds) is frequently used to define the fidelity to which it is desirable to represent the NWDS with sensors or to emulate it with computers. However, this rule of thumb has two significant drawbacks. First, as shown in Tables I and Table II, virtually every one of the some 6 billion sighted persons on earth sees better than 20/20. Second, users of displays in specialty applications frequently have much better vision than the general population and, also, receive training to more effectively use their vision.

Clearly, electronic displays can be improved through many generations, just as have microchips.

Table II. Superiority of the natural world, real human vision system, relative to the normal 20/20 vision metric.

Parameter	20/20 vision	Natural world / HVS
Ambient	Fixed at ~10 lx	10^7 range (10^{-3} to 10^{+5} lx)
Grayscale	1 bit (on/off)	20 bits (shading nuances)
Color	No (black/white)	Yes (full, > 32 M colors)
Motion	No (static)	Yes (> 100 Hz)
Content	Very low (letters)	Very complex (real world)
Peripheral	No	Yes
Latency	Zero (static image)	Zero (moving image)

Discussion

Display technology of today would get a grade of "F" compared to the NWDS or the computer chip industry. Sampling at smaller increments of space, intensity, and time is needed to address the differences between the NWDS/HVS and current (year 2002) displays. That is, current TFT-on-glass technology needs to scale down to smaller pixel sizes even as display size increases. Research exists for specialty applications in other directions too, including

- fabrication on flexible substrates like steel and plastic;
- fabrication of curved versus flat projection μ-displays;
- manufacturing of TFT plates and other subcomponents via printing techniques to dramatically reduce costs;
- fabrication via fluidic transport techniques to enable different semiconductor materials and circuits fabricated in high-temperature microelectronics fabs to be put on low-temperature substrates for displays in display fabs;
- move functionality now residing on processor boards in microprocessor chips and focal plane arrays into the display device structure (intelligent pixels/displays).

Information technology (IT) industry growth requires improved capabilities for image capture and sensing, generation and processing, communication and transmission. But the main limitation to better IT products is better display technology. Leglise [4] of Intel, for example, has declared the need for displays to begin developing at a Moore's law rate, with pixels in each device doubling each 18 months.

The scientific supercomputing community is fueling the development of seamless tiling to enable creation of ultraresolution systems and vision-ariums to enable scientists to interact in some meaningful way with the gigantic databases generated in fields like astronomy and nuclear power fusion modeling. These systems approach resolutions of 100 million pixels, or one hectomegapixel (HMP). Multi-HMP systems are needed too for realistic aircraft out-the-window simulators and complete audio-visual environments for education and entertainment. See Figure 2.

Specialty applications will continue lead efforts to improve display technology and will drive future commonalty applications with new insights and techniques. Companies with mass market fabs that fail to provide some sufficient level of effort in support of exotic and niche markets may not survive many years in the display business.

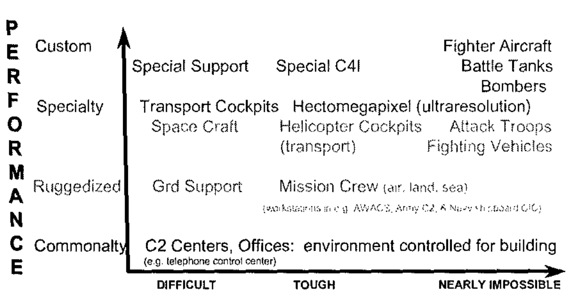

Figure 2. System performance versus design class.

Challenges

The challenge to all display technologies in all applications is to close the fantastic gap between the capacity of the human visual system and currently available products. Simple 20/20 vision is over 100 times the resolution of current technology; and most people see better than 20/20 implies.

The specialty display challenge is to leverage commonalty markets like notebooks, monitors, internet appliances, and mobile devices to the maximum extent possible. Non-ordinary applications must adapt by applying relative small amounts of funding to achieve low volume but high performance products. Some 81% of all displays within defense systems are mass-market products designed for commonalty applications but ruggedized (integrated) into military display products. Only the remaining 19% of defense display devices require custom design and manufacture to achieve the form factor and performance mandated by a higher-level optimization at the weapon-system level. And this 19% is produced using a business model comprising an aggregator of defense OEM orders who then arranges for fab time at a mass production facility. See also Figures 1 and 2.

Specialty applications grow daily. The revolution in display technology has just begun. Aerospace applications began in 1988 with the introduction of the Toshiba 2.5 x 2.5 in. specialty display for the commercial aircraft transport collision avoidance system, and have now grown to the 7.8 x 7.8 in. specialty display in the F-22A Raptor cockpit. Specialty ultraresolution displays now range from 9 Mpx devices to 72 Mpx tiled systems [5,6]. It is now time to prepare for panoramic cockpits, ultrahigh resolution simulators, and immersive entertainment rooms. Research goals include establishment 36 Mpx and flexible displays with embedded intelligence by 2005, and 230Mpx visualization systems by 2010.[2,3,7]

References

[1] D.G. Hopper, "Performance specifications: the nearly impossible versus the mearly difficult," Proceedings of SPIE Vol. 4022, pp. 38-49 (2000).

[2] D.G. Hopper, "A Vision of Displays of the Future," in *SID Electronic Information Displays Conference Digest of Technical Papers*, Esher, Surrey, UK, 4 pp., 16-18 Nov (1999).

[3] D. G. Hopper, "1000 X difference between current displays and capability of human visual system: payoff potential for affordable defense systems," Proceedings of SPIE Vol. 4022, pp. 378-389 (2000).

[4] Claude Leglise, "It's All About the Eyeballs," plenary presentation at SID International Symposium, June (2001).

[5] T. Ueki, "Requirements for Large Size and High Resolution TFT-LCDs," in *Proceedings of The 1st International Display Manufacturing Conference*, Paper 11.1, pp. 177-180, 5-7 Sep (2000).

[6] 72-megapixel PARAllel Displays for Image and Graphics Manipulation (PARADIGM) comprising 96 XGA TFT LCDs, build by KAIST in Taejon, installed in 3rd floor lobby of SK building in Seoul, Korea. www.kaist.ac.kr

[7] D. G. Hopper, "Five Revolutions in Display Technology: Sharpness, Digital, Resolution, True-3D, and Intelligence," in *3-D Vision & Advanced Display Workshop,* Industrial Technology Research Institute, Hsinchu, Taiwan, March (2001).